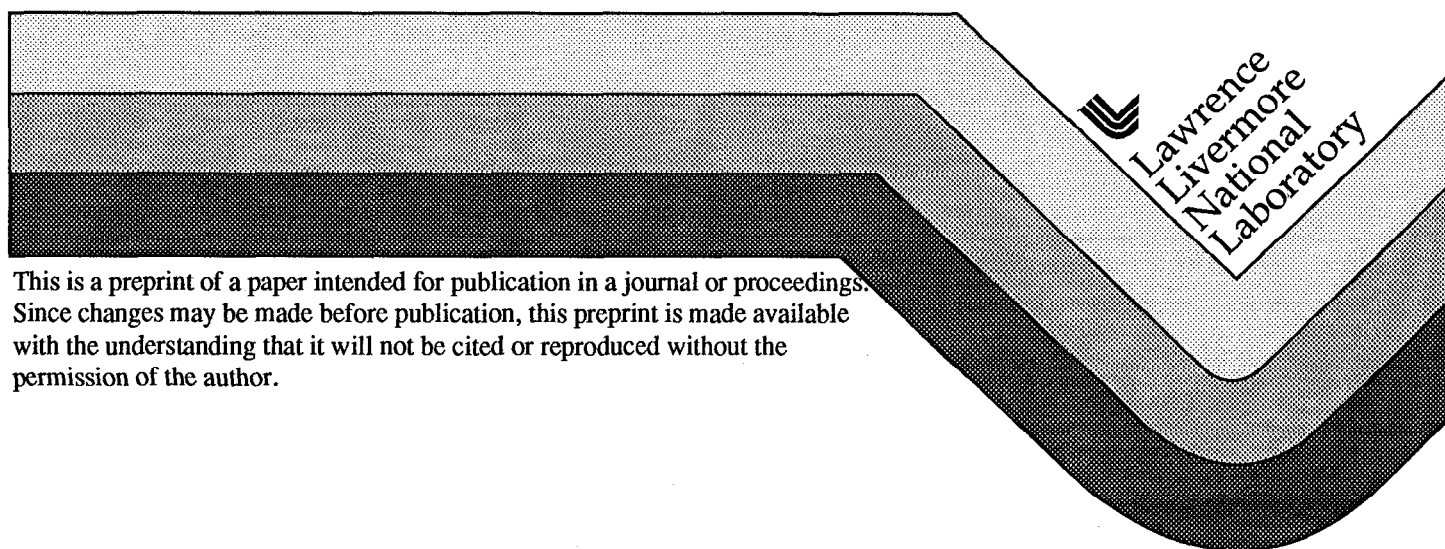


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Development of a Radiative-Hydrodynamics Testbed using the Petawatt Laser Facility¹

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ABSTRACT

Many of the conditions believed to underlie astrophysical phenomena have been difficult to achieve in a laboratory setting. For example, models of supernova remnant evolution rely on a detailed understanding of the propagation of shock waves with gigabar pressures at temperatures of 1 keV or more where radiative effects can be important. Current models of gamma ray bursts posit a relativistically expanding plasma fireball with copious production of electron-positron pairs, a difficult scenario to experimentally verify. However, a new class of lasers, such as the Petawatt laser, Perry 1996 are capable of producing focused intensities greater than 10^{20} W/cm² where such relativistic effects can be observed and even dominate the laser-target interaction. There is ample evidence in observational data from supernova remnants of the aftermath of the passage of radiative shock or blast waves. In the early phases of supernova remnant evolution, the radially-expanding shock wave expands nearly adiabatically since it is traveling at a very high velocity as it begins to sweep up the surrounding interstellar gas. A Sedov-Taylor blast wave solution can be applied to this phase, Taylor 1950, Sedov 1959 when the mass of interstellar gas swept up by the blast greatly exceeds the mass of the stellar ejecta, or a self-similar driven wave model can be applied if the ejecta play a significant role. Chevalier 1982 As the mass of the swept up material begins to greatly exceed the mass of the stellar ejecta, the evolution transitions to a radiative phase wherein the remnant can be modeled as an interior region of low-density, high-pressure gas surrounded by a thin, spherical shell of cooled, dense gas with a radiative shock as its outer boundary, the pressure-driven snowplow. Blondin et al. 1998 Until recently it has not been feasible to devise laboratory experiments wherein shock waves with initial pressures in excess of several hundred Mbar and

temperatures approaching 1 keV are achieved in order to validate the models of the expanding blast wave launched by a supernova in both of its phases of evolution.

We report on a new experiment designed to follow the propagation of a strong blast wave launched by the interaction of an intense short pulse laser with a solid target. This blast wave is generated by the irradiation of the front surface of a layered, solid target with ~ 400 J of $1\ \mu\text{m}$ laser radiation in a 20 ps pulse focused to a $\sim 50\ \mu\text{m}$ diameter spot, which produces an intensity in excess of $10^{18}\ \text{W}/\text{cm}^2$. These conditions approximate a point explosion and a blast wave is predicted to be generated with an initial pressure of several hundred megabars which decays as it travels approximately radially outward from the interaction region. We have utilized streaked optical pyrometry of the blast front to determine its time of arrival at the rear surface of the target. Applications of a self-similar Taylor-Sedov blast wave solution allows the amount of energy deposited to be estimated. By varying the parameters of the laser pulse which impinges on the target, pressures on the order of 1 Gbar with initial temperatures in excess of 1 keV are achievable. At these temperatures and densities radiative processes are coupled to the hydrodynamic evolution of the system. Short pulse lasers produce a unique environment for the study of coupled radiation-hydrodynamics in a laboratory setting.

Subject headings: hydrodynamics, shock waves, supernova remnants

1. Introduction

The universe is filled with examples of strong, radiative shock waves interacting with their surroundings. For example, a red super giant supernova in the supernova remnant phase is characterized by a shock wave propagating radially outward from the collapsed core of the progenitor star. Radiative effects are manifested in two ways in this system. Radiation leaving the hot shocked plasma cools this region and acts as a radiative precursor which preheats the plasma in front of the shock. This effect is illustrated in one dimension in Figure 1. The detailed evolution of such a system becomes even more complex when examined in two dimensions. The evolution of blast waves generated by laser ablation of solid targets has been studied by numerous groups in fields as widely divergent as materials processing and astrophysics.[Grun et al. 1991, Kyrala et al. 1990, Matsuo and Nakamura 1980, Diaci and Mozina 1992, Couturier et al. 1996, Aden et al. 1997] Depending on the Mach number ($M = v_{\text{shock}}/c_{\text{sound}}$) of the shock and the rate of radiative cooling present as defined by the cooling curve

$$\Lambda = \Lambda_o T^\alpha \tag{1}$$

where α is a fitting parameter and $n^2\Lambda$ is ergs/cm³-sec of cooling with n being the density, the shock front is susceptible to “overstabilities”. [Vishniac 1983, Ryu and Vishniac 1991, Grun et al. 1991, Draine and McKee 1993, McKee and Draine 1991, Shull and McKee 1979, Strickland and Blondin 1995] Laboratory experimental tests of the models of radiative shocks are difficult to construct since, for optically thick systems, the plasma must be very hot ($T_e \sim 1$ keV) in order for radiative effects to significantly alter the hydrodynamic evolution of the system. In the case of an optically thin system a short radiative time scale is characterized by a lower temperature but high density. However, eventually raising the density will cause the system to become optically thick to radiation, making these conditions difficult to generate in the laboratory.

However, a new generation of short pulse lasers,[Perry 1996] capable of generating intensities in excess of 10^{18} W/cm², has allowed us to begin investigating a variety of physical processes including radiative shock waves in detail. At such intensities, the accelerated hot electron temperature distribution in the hot spot of the plasma generated by the laser-solid target interaction is believed to be a 200 keV Maxwellian with a tail extending out well beyond 1 MeV and the pressure is predicted to be ~ 1 Gbar.[Key et al. 1998] Detailed simulations of the laser-target interaction indicates that roughly 50% of the incident laser energy is absorbed by the target and the remainder is reflected back off of the critical surface of the plasma formed. Approximately 40% of this absorbed energy is predicted to be deposited into the electrons which propagate away from the laser spot.[Wilks and Kruer 1997, Wharton et al. 1998] As these electrons move away from the interaction region, a large potential is generated due to the ions left behind which serves to retard the forward motion of the electrons. Initially, only a small amount of the incident energy ($\sim 2-3$ %) is deposited into the ions. Over several hundred picoseconds, the electrons transfer energy to the ions and come into equilibrium and a strong blast wave is launched. Because of the small size of the spot into which the laser energy is deposited, it is well-approximated by a point explosion and the blast wave settles into an adiabatic expansion described by the self-similar Sedov solution where the position of the blast wave is given by

$$r_{\text{blast}}(t) = f(\gamma)E^{1/5}t^{2/5} \quad (2)$$

where $f(\gamma)$ is a coefficient dependent upon the material equation of state, E is the energy deposited and t is time.[Sedov 1959, Taylor 1950, Zel'dovich and Raizer 1966]

The interaction is illustrated schematically in Figure 2. The trajectory of the spherically-expanding blast wave is a direct measure of the energy deposited within the laser spot through Equation 1. Simulations indicate that the hot electrons tend to bunch together in filaments which may produce localized inhomogeneities in the material into which the

blast wave propagates. Any deviation from a smooth, roughly spherical front could be an indication of the distribution of these electron filaments. Therefore, this diagnostic is potentially a unique, direct probe of the partition of energy in the initial interaction.

2. Experimental Configuration and Data

The blast wave studied herein was generated by focusing the pulse generated by the Petawatt laser system[Perry 1996] onto the surface of a solid plastic target. The experimental schematic is shown in Figure 3. The incident laser pulse was 400 J at $1\ \mu\text{m}$ wavelength and had a temporal duration of 20 psec. The pulse was focused to a $\sim 50\ \mu\text{m}$ spot by an f/3 parabola resulting in an intensity of approximately $1 \times 10^{18}\ \text{W}/\text{cm}^2$. The target consisted of a $5\ \mu\text{m}$ CH ablator backed by $0.5\ \mu\text{m}$ of aluminum (utilized for a spectroscopic diagnostic) and finally $400\ \mu\text{m}$ of deuterated polystyrene (CD_2). An f/10 Cassegrain telescope (Questar QM1) placed 1 m from the target images the rear surface of the target.

The first attempt at a blast wave measurement wherein the image from the telescope was cast directly onto the slit of an optical streak camera placed on a direct line-of-sight to the target was unsuccessful due to a high background level from the copious amounts of hard x-ray and hot electrons produced by the laser-target interaction. The configuration was modified to remove the streak camera from proximity to the target chamber by constructing a 10 ft vertical periscope and a 2-inch-thick wall of lead was installed between the target chamber and the detector. Thus, any high energy photons or electrons present pass through the first turning mirror in the periscope and leave the system. The observing bandwidth of the optical system is centered around $\sim 350\ \text{nm}$ ($T_r \sim 3\ \text{eV}$).

Figure 4(a) shows a raw image of the data and an averaged lineout through this image

is contained in Figure 4(b). The data show two interesting features. First a weak prompt signal is observed which is correlated to the arrival of the intense laser pulse at the surface of the target. This may be caused by the initial burst of hot electrons rapidly heating the rear surface of the target to several eV, a very small temperature rise relative to the temperature at the front surface plasma. After 4.9 ns a very strong signal, which saturated the streak camera, is observed due to the breakout of the blast wave from the rear surface of the target. Another interesting feature is the lower intensity signal which precedes the blast wave by several hundred picoseconds. This may be the signal of the precursor caused by radiation from behind the blast front. Because of the high signal level, no definitive determination of the shape of the breakout can be made.

3. Theory and Simulations

Figures 5(a),(b) and (c) show the results of a LASNEX[Zimmerman and Kruer 1975] simulation of this experiment.[Estabrook et al. 1998] This simulation was initialized by depositing 180 J in a Maxwellian distribution of electrons with a peak at 144 keV into a 44 μm diameter spot over 20 psec. The density profiles shown in Figure 5(a) (.1 - .5 ns) and (b) (1 - 4.1 ns) show that by ~ 0.5 ns the hydrodynamic blast wave has formed and begun to propagate through the target. It reaches the rear surface at ~ 4.1 ns, in rough agreement with the observations. Figure 5(c) shows the evolution of T_r , or radiation temperature from very early times (.01 - .1 ns) where a distinctive radiative precursor is observed to later times (1 - 4.1 ns) where the temperature preceding the blast front is negligible.

Since we have only experimentally measured a single point along the trajectory of the blast wave, we compare the results of the LASNEX simulations to the Sedov prediction. Figure 6(a) shows the blast wave trajectory from LASNEX as a function of time (solid circles) compared to the Sedov solution (solid line) where the prefactor $f(\Lambda)$ has been

adjusted to match the simulations. At times greater than 1 ns the blast wave appears to be evolving adiabatically. However, at earlier times the influence of the radiation field can be seen as shown in Figure 6(b). Here the time period from 0 - 1.5 ns and distances from 200 to 300 μm are shown. Significant departures from the Sedov prediction are observed in this early stage indicating that perhaps the initial phase of the blast wave evolution is altered by radiation from behind the blast wave front or the finite size of laser focal spot.

4. Conclusions and Future Directions

We have made the first direct observation of the blast wave launched by the interaction of the Petawatt laser with a solid target. Such observations may provide a direct measure of how the laser energy deposited into the target is partitioned between hydrodynamic coupling, a forward-directed jet of hot electrons and energy radiated away from the hot surface plasma. Initial results are in reasonable agreement with LASNEX simulations. The LASNEX simulations have been compared with a Sedov solution for an adiabatically expanding blast wave and show good agreement except for early times when radiative effects and the finite laser focal spot size may be important.

Future experiments will attempt to experimentally map the trajectory of the blast wave by varying the thickness of the target. Additionally, a portion of the Petawatt laser beam may be directed onto a secondary target to generate an x-ray backlighter which may allow us to record a 2-dimensional image of the blast wave in flight. Deviations from a spherical shape may be indicative of the influence of the hot electron jet or the presence of instabilities on the blast wave front.

Experiments of this type can be used to validate the radiation hydrodynamic models of evolving supernova remnants in both the adiabatic and, potentially, the radiative phase

of their evolution in regimes of pressure and radiation temperatures not readily achievable in a laboratory prior to the advent of high-power, short pulse lasers.

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REFERENCES

- Aden, M., Kreutz, E. W., Schluter, H., and Wissenach, K., 1997, *J. Phys. D.*, 30, 980
- Blondin, J. M., Wright, E. B., Borkowski, K. J., and Reynolds, S. P., 1998, *ApJ*, 500, 342
- Chevalier, R. A., 1982, *ApJ*, 258, 790
- Couturier, S., Derresseguier, T., Hallouin, M., Romain, J. P., and Bauer, F., 1996, *J. Appl. Phys.*, 79, 9338
- Diaci, J. and Mozina, J., 1992, *Opt. Commun.*, 90, 73
- Draine, B. and McKee, C., 1993, *ARA&A*, 31, 373
- Estabrook, K. G., in the proceedings of the 2nd International Workshop of Laboratory Astrophysics with Intense Lasers, 19-21 March 1998, Tucson, AZ.
- Grun J., Stamper, J., Manka, C., Resnick, J., Burris, R., and Ripin, B. H., 1991, *Appl. Phys. Lett.*, 59, 246
- Grun, J., Stamper, J., Manka, C., Resnick, J., , 1991, *Phys. Rev. Lett.*, 66, 2738
- Key, M. H., Cable, M. D., Cowan, T. E., Estabrook, K. G., Hammel, B. H., Hatchett, S. P., Henry, E. A., Hinkel, D. E., Kilkenny, J. D., Koch, J. A., Kruer, W. L., Langdon, A. B., Lasinski, B. F., Lee, R. W., MacGowan, B. J., MacKinnon, A., Moody, J. D., Moray, M. J., Offenberger, A. A., Pennington, D. M., Perry, M. D., Phillips, T. J., Sangster, T. C., Singh, M. S., Stoyer, M. A., Tabak, M., Tietbohl, G. L., Tsukamoto, M., Wharton, K., and Wilks, S. C., 1998, *Phys. Plasmas* 5, 1966
- Kyrala, G., Lee, P. H., Stetler, K. A., and Yu, I. I., 1990, *Proc. SPIE*, 1155, 475
- Matsuo, H. and Nakamura, Y. , 1980, *J. Appl. Phys.*, 51, 3126

- McKee, C. F., and Draine, B. T., 1991, *Science* 252, 397
- Perry, M. D., *Science and Technology Review*, 1996, UCRL-52000-96-12
- Ryu, D. and Vishniac, E., 1991, *ApJ*, 368, 411
- Sedov, L. I., 1959, *Similarity Dimension*
- Shull, J. M., and McKee, C. F., 1979, *ApJ*227, 131
- Strickland, R., and Blondin, J. M., 1995, *ApJ*449, 727
- Taylor, G. I., 1950, *Proc. Royal Soc. London A* 201, 159
- Vishniac, E. T., 1983, *ApJ*27, 152
- Wharton, K., 1998, accepted for publication in *Phys. Rev. Lett*
- Wilks, S. C. and Kruer, W. L., 1997 *IEEE J. Quant. Electron.* 33, 1954
- Ya. B. Zel’dovich and Yu. P. Raizer, *Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena*, edited by W. D. Hayes and R. F. Probstein (Academic Press, San Diego, 1966), vol. 1, P. 94.
- Zimmerman, G. B. and Kruer, W. L. , 1975, *Comments Plasma Phys. Controlled Fusion* 2, 51

Fig. 1.— Diagram of the propagation of a radiative shock wave showing the effect of the radiation on the temperature, density and velocity of the shock front.

Fig. 2.— Illustration of the interaction of the high-intensity laser pulse with the solid target and subsequent hot electron and blast wave propagation. E_1 denotes energy hydrodynamically-coupled into the target in the form of a blast wave.

Fig. 3.— Schematic of the experimental configuration for the Petawatt blast wave measurement.

Fig. 4.— (a) Raw image of the data from the streaked optical pyrometer. (b) Averaged lineout through the image showing intensity in arbitrary units versus time.

Fig. 5.— LASNEX simulations of the density (g/cm^3) as a function of depth in the target from (a) .1 - .5 ns and (b) 1 - 4.1 ns. (c) LASNEX simulations of the radiation temperature (T_r in eV) as a function of depth in the target for a variety of times.

Fig. 6.— (a) Comparison of the blast wave trajectory as a function of time predicted by LASNEX to the self-similar Sedov solution. (b) Here the predicted blast wave trajectory for the first 1 ns of its evolution is plotted versus $t^{2/5}$ showing significant deviations from the Sedov prediction at early times.

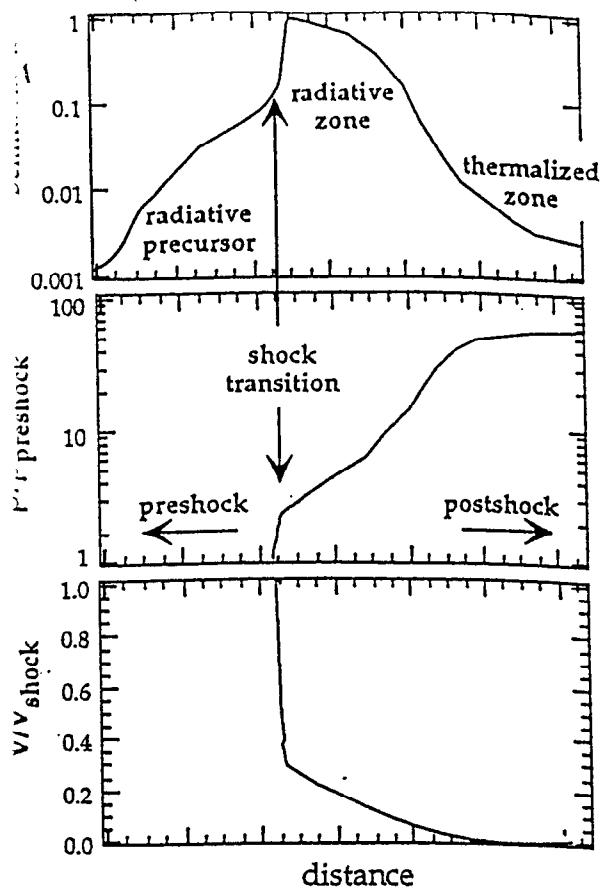


Fig. 1

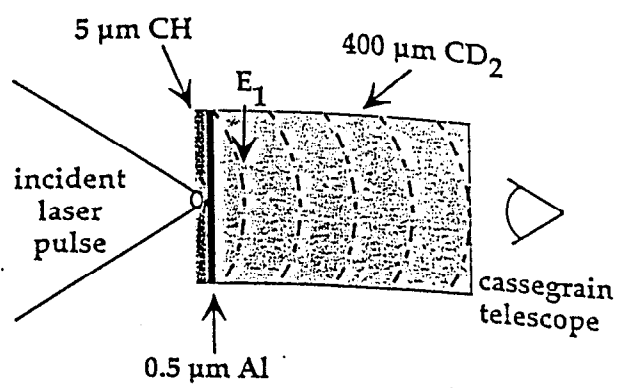


Fig. 2

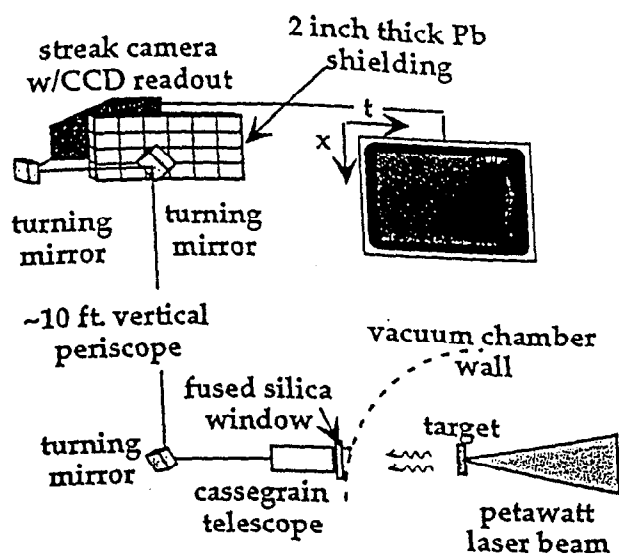
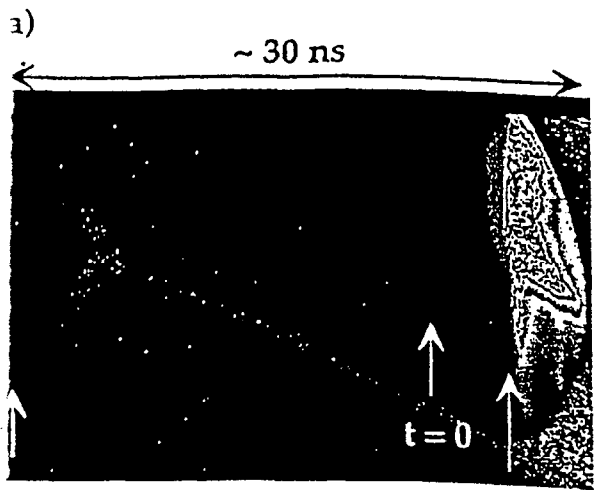


Fig. 3



start of streak camera sweep

shock breakout

(b)

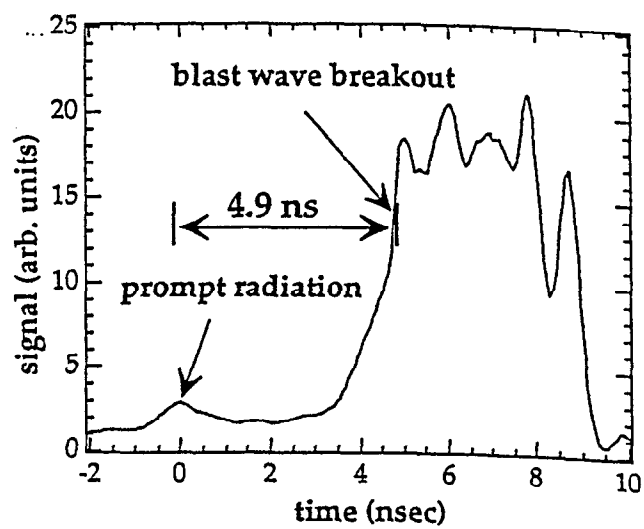
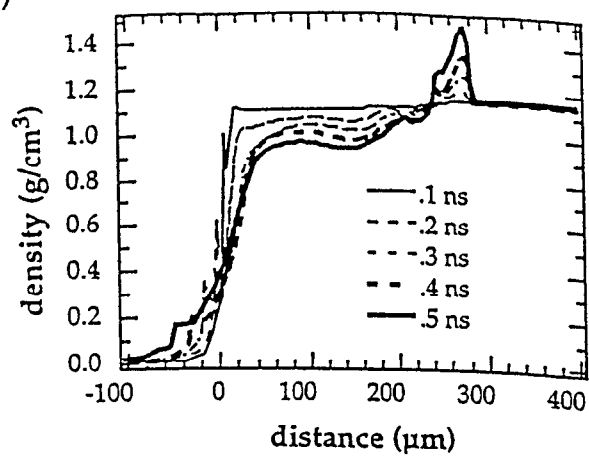
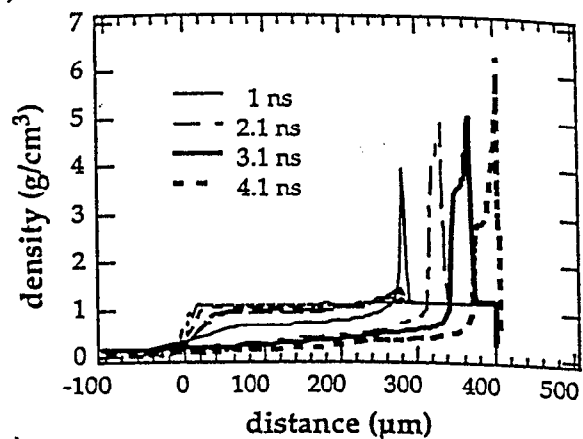


Fig. 4

(a)



(b)



(c)

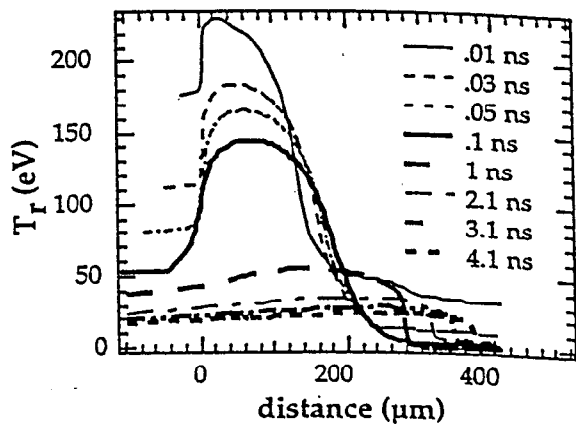
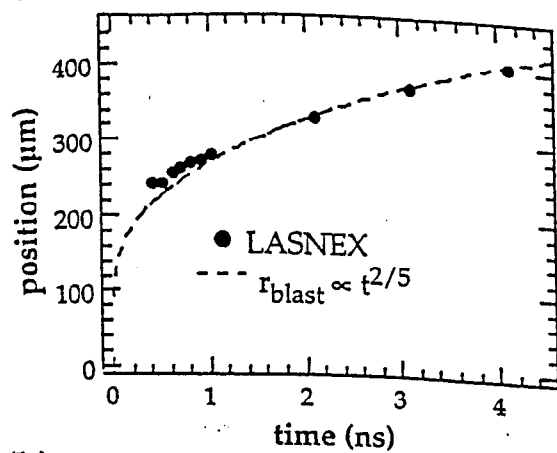


Fig. 5

(a)



(b)

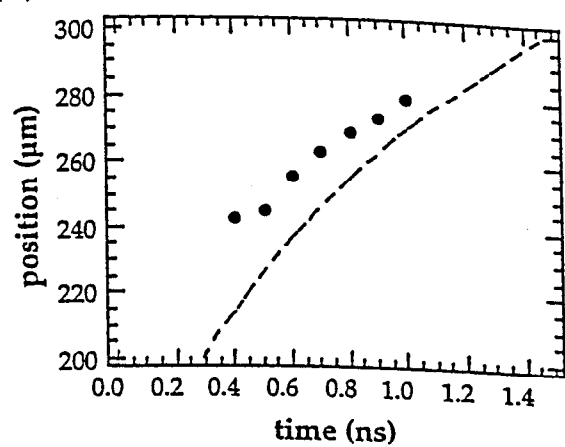


Fig-6